Cloud Shortwave Radiative Forcing from Satellite and Surface Data During the ARM Enhanced Shortwave Experiment

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Introduction

Cloud absorption of solar radiation has been the focus of several recent studies and the Atmospheric Radiation Measurement Program (ARM) Enhanced Shortwave Absorption Experiment (ARESE). One of the methods for studying cloud absorption has employed the analysis of coincident surface and satellite measurements. To provide consistency with the earlier satellite results, this paper presents the results of an analysis using Geostationary Operational Environmental Satellite (GOES) data and measurements taken during ARESE at ten surface sites.

Data

The ARESE was conducted from September 25 through November 1, 1995, as part of the ARM Unmanned Aerospace Vehicle Program. Half-hourly GOES-8 narrowband visible and infrared data were analyzed following the methods of Minnis et al. (1995) to derive clear-sky and cloud radiative properties for 0.3° boxes centered on ten surface radiometer sites maintained by ARM or deployed temporarily during ARESE. The adjusted nominal visible-channel calibration was applied to the GOES-8 data (Ayers et al. 1996) to derive visible (VIS) radiances. These radiances were converted to VIS albedo

$$\alpha_v = \pi L_8 / [\delta(d) \mu_o E_8 \chi(\mu_o,\mu,\phi), \quad (1)$$

where δ is the Earth-Sun distance correction factor for Julian day d, E_8 is the solar constant for the G8 channel, μ_o and μ are the cosines of the solar and satellite zenith angles, ϕ is the relative azimuth angle, and χ is the anisotropic directional model which depends on the background. Values for χ were taken from the models of Minnis and Harrison (1984).

The broadband albedo α_b was computed from α_v using a set of conversion formulae derived from correlations of GOES-6 and Earth Radiation Budget Satellite (ERBS) albedos taken over the southern Great Plains (95°W -105°W; 32.5°N - 42.5°N) during October 1986. These correlations are shown in Figure 1. Each point represents an average over a 2.5° region. For all of the data,

$$\alpha_b = 0.101 + 0.853 \alpha_v - 0.130 \alpha_v^2 + 0.042 \ln(1/\mu_o). \quad (2)$$

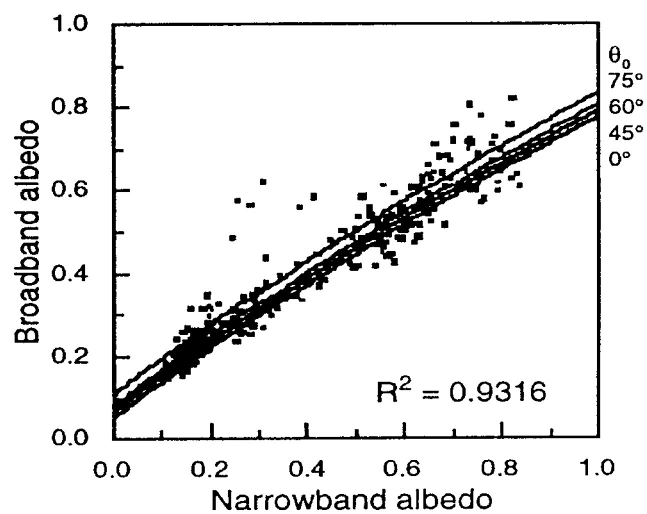

Figure 1. Correlation of GOES-6 visible and ERBS shortwave albedos over the Southern Great Plains.

The surface flux data consist of up- and downlooking broadband shortwave measurements at the ten locations mappedin Figure 2. The instruments were situated over a variety of surface vegetation and soils and underneath the typical flight tracks of the ARESE aircraft. The high-frequency irradiance data from each site were averaged at half-hourly intervals centered on the satellite image times. Only data from October 18-29 were used from the Kyle site because of siting problems before the 18th.

Analysis

The analysis method follows that of Cess et al. (1995). The instantaneous top-of-the-atmosphere (TOA) cloud forcing is

$$TCRF_i = E_o(\delta)\mu_o(\alpha_{cld} - \alpha_{clr}), \quad (3)$$

where E_o is the solar constant, δ is the relative Earth-Sun distance, and μ_O is the cosine of the solar zenith angle (SZA). Similarly,

$$SCRF_i = M{\downarrow}_{sclr} - M{\downarrow}_{scld}, \quad (4)$$

is the instantaneous insolation forcing at the surface. The ratio of TOA to surface cloud radiative forcing for the ARESE period is

$$R = \frac{SCRF}{TCRF}, \quad (5)$$

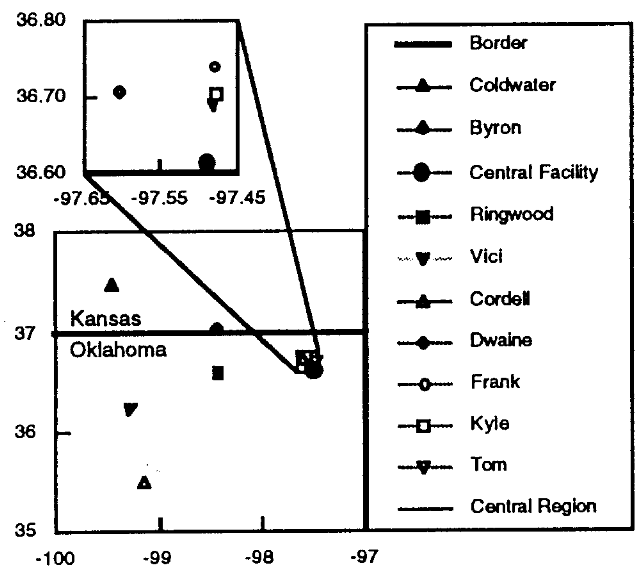

Figure 2. Configuration of ARESE surface sites.

where SCRF and TCRF are the sums of $SCRF_i$ and $TCRF_i$ for all paired surface and satellite data. Clear-sky insolation and TOA albedo were determined using the linear regression method of Cess et al. (1995).

That technique produced values of α_{clr} and $M{\downarrow}_{sclr}$ that are nearly identical to those determined from more labor-intensive and rigorous methods (e.g., Minnis et al. 1995).

Another measure of the cloud forcing is the mean rate of change of TOA albedo with transmission at the surface $T = M{\downarrow}_{sclr} / [\mu_o E_o(\delta)]$. This slope β is determined by linear regression using all instantaneous values of the two quantities.

Results

The shortwave cloud forcing data for the ARM Central Facility are plotted in Figure 3 with the clear-sky regression

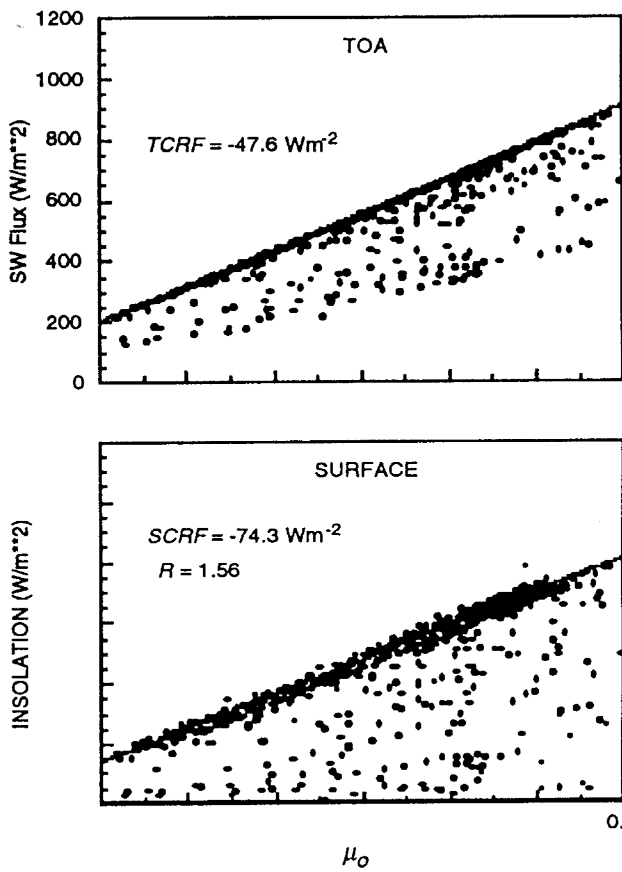

Figure 3. Cloud radiative forcing over the ARM SCF during ARESE from GOES-8 and tower radiometer data.

lines. Clear-sky albedo is much less variable than the surface insolation about the regression although the correlation coefficient is 0.99 for the surface data. The value of R = 1.56 is typical of the values found for the other sites where R ranged from 1.31 at Kyle to 1.82 at Cordell (Figure 4). Figure 4 also shows the net cloud forcing ratio R(net) for each site. This parameter is the same as R except that net flux at the surface is used instead of the insolation. The values of R(net) vary from 0.97 at Tom to 1.47 at Cordell. The correlation coefficients for the fit to the clear surface net and insolation were 0.95 or greater for all sites except Coldwater and Kyle, where they were 0.91. The average values of R and R(net) for all sites are 1.55 and 1.20, respectively.

Figure 5 shows a scatterplot of α_{TOA} and T with the linear regression fit for the SCF. The values of β range from -0.58 at Byron to -0.70 at Tom (Figure 6). Overall, the mean slope is -0.614. The value of R(net) can also be computed as $-(1 - \alpha_{sfc})/\beta$, where α_{sfc} is the mean surface albedo. The average value computed in this manner, 1.27, is very close to R(net) derived earlier. The differences between the two methods range from -0.11 to 0.11. The only zero difference occurred for the SCF data. Surface albedos varied from 0.15 at Frank to 0.27 at Tom. At the SCF, α_{sfc} = 0.214 compared to α_{clr} = 0.195.

Discussion & Conclusions

Based on Figures 3 and 4, it may be concluded that the addition of clouds to the atmosphere over Oklahoma increases the atmospheric absorption by 0 to 22 Wm^{-2} for daytime only. The mean increase for all sites is 20% or ~10 Wm^{-2}. For a 24-hr day, this change reduces to less than 5 Wm^{-2}. Cess et al. (1995) found a mean value for R(net) of 1.46 for data taken over other areas. The current results suggest that the increase in absorption due to clouds over this region is approximately half that found in the earlier study. This discrepancy is consistent with differences in β found here and by Cess et al. (1995). However, recent results from Cess et al. (1996) and Imre et al. (1996) show a smaller cloud

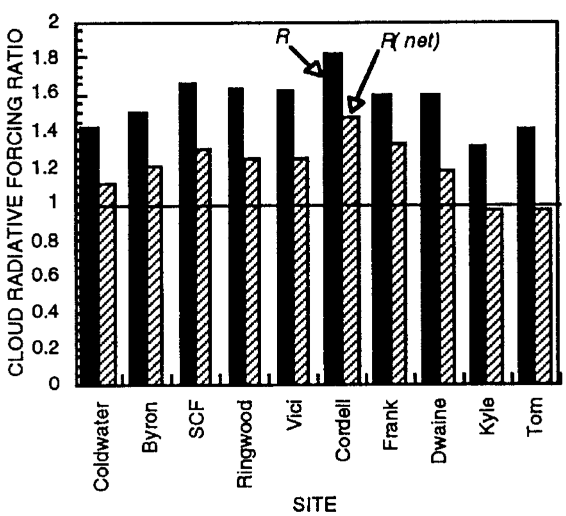

Figure 4. Satellite-surface cloud radiative forcing ratios over the ARESE sites.

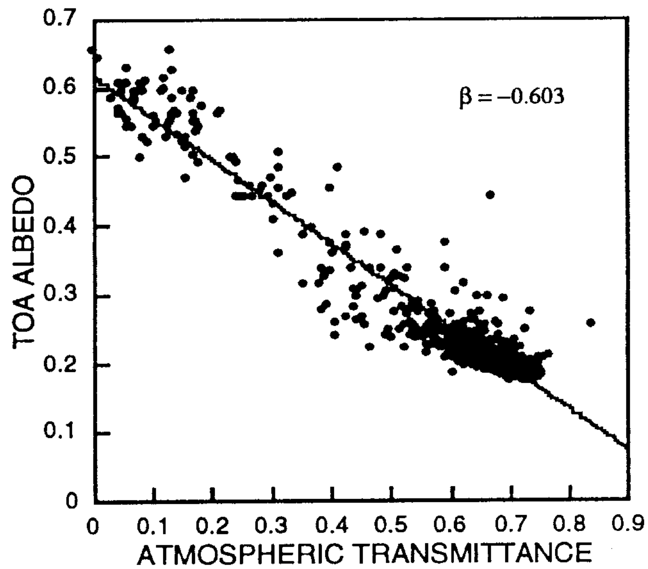

Figure 5. Correlation of satellite-derived albedo and atmospheric transmittance to the surface at the SCF.

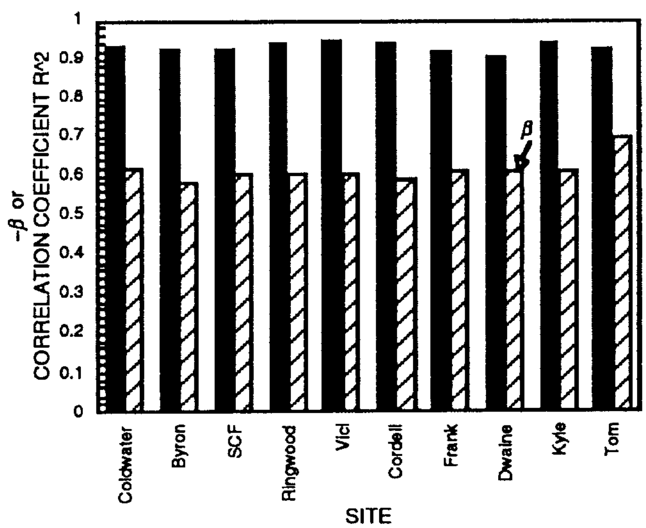

Figure 6. Albedo-transmission correlation coefficients over ARESE sites.

absorption effect for the SCF area based on the April 1994 results of Minnis et al. (1995). The former found β = -0.64 which is 4% higher than the present average. The Imre et al. (1996) study reported that the absorption increased from 22.4% of the total insolation for clear skies to 26.2% in cloudy skies, an absorption increase of 17%. Both results are within the range of values found here.

Typical model calculations of R and β for the Oklahoma area are 1.3 and -0.76 (Cess et al. 1996). The differences between the model estimates and the observations suggest that more solar radiation is absorbed in a cloudy atmosphere than currently suggested by theory but less than estimated earlier. Despite the disagreements in the magnitude, the sign of the model-observation differences is the same for most studies.

The observations presented here are based on a nominal calibration of the GOES-8 visible channel. A 10% increase in the visible channel gain would increase β by a similar amount. Such an increase would decrease the magnitude of the model observation discrepancy. It would not alter the sign of the difference. Further analysis will be performed after the GOES and surface radiometer calibrations are completed. These results provide a critical part of the analysis needed to understand the apparent anomalous absorption in cloudy skies.

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